Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2015) 23: 1284 – 1293

doi:10.3906/elk-1304-195

A novel asymmetrical connection balance transformer for traction power supply

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Received: 20.04.2013 • **Accepted/Published Online:** 02.08.2013 • **Printed:** 28.08.2015

Abstract: Balance transformers can usually eliminate the zero sequence current and suppress the negative sequence current. This paper develops a novel approach for balance transformers, which is different from the traditional one with two-phase or three-phase symmetrical windings. First, the basic principle and the connected scheme of the transformer are clarified. Second, this paper derives the relationship between the primary and the second windings from a mathematical model for the new approach. Third, the balance condition (i.e. the neutral current in the primary side is zero) and the decoupling condition of the two-phase system are also obtained. Finally, the correctness and feasibility of the new approach are verified by the experimental results of a 1-kVA model transformer. Compared to the traditional balance transformers, the new approach has better performance and can be applied to the two-phase or single power supply, such as the traction power supply in electric railway.

Key words: Connection scheme, balance condition, asymmetrical winding, traction power supply

1. Introduction

Conventional systems of power transmission and distribution are three-phase systems. In some cases, however, single-phase or two-phase power supply is required [1–3]. This certainly will cause three-phase systems to operate asymmetrically, producing large negative sequence current and zero sequence current, which lower the power supply quality and influence the power supply for other users. The asymmetric operation is particularly serious in the traction electric network of electric railways. As for the three-phase electric networks of 110 kV or above, the transformer generally operates in the mode of neutral-point grounded in order to reduce the voltage insulation level. The high-voltage neutral current (zero sequence current) produced by the unbalanced load of the transformer is required to be in the range of allowable values.

The three-phase to two-phase balance transformer is a broadly applicable approach to reduce or eliminate negative sequence current and zero sequence current. Using the balance transformer, the two-phase secondary currents can result in balanced three-phase currents on the primary side under some specific load conditions. The traditional balance transformers include Scott, Le Blanc and Woodbridge, as well as the impedance-matching balance transformer [4–6]. These balance transformers are shown in Figure 1. There are also certain disadvantages associated with these transformers. First of all, the material (iron and copper) utilization factors of these transformers are relatively low. The material utilization factors of Scott, Le Blanc, and Woodbridge transformers are only 81.6%, 84.5%, and 82.6%, respectively. Meanwhile, the required voltage insulation level is high and costly for the Scott and Le Blanc transformers, since there is no neutral point in the primary windings of these transformers. Furthermore, the Woodbridge transformer needs two additional autotransformers for the

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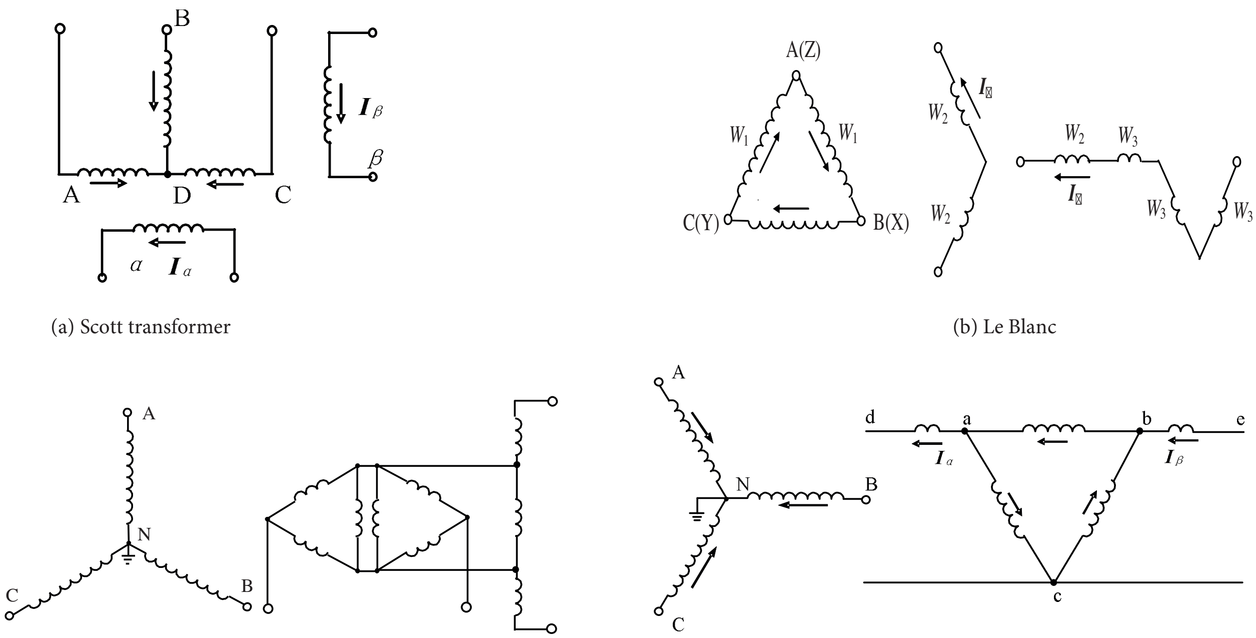
two-phase railway traction power supply [7–10]. Additionally, there is a voltage distortion in the two-phase output of the Scott transformer, since it does not possess a delta connection. The third-harmonic currents and voltages exist with this connection. Lastly, the impedance-matching balance transformer [11–14], the most applied one in China, has four windings in the B-phase, which results in a degree of winding complication.



(a) Scott transformer (b) Le Blanc

(c) Woodbridge (d) Impedance-matching

Figure 1. Connection diagrams of the typical balance transformers.

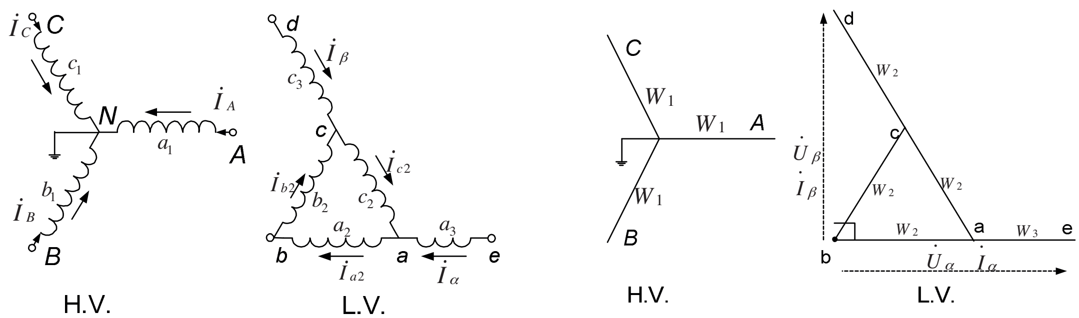
Compared to the balance transformers, the V/V connection scheme has inferior performance in reducing the three-phase unbalance since it is inherently unbalanced [15]. For the traditional transformers, three-phase windings or two-phase windings are symmetrical. A novel three-phase to two-phase balance transformer with three-phase asymmetrical windings is going to be presented in this paper.

The rest of this paper is organized as follows. Section 2 explains the wiring scheme and the basic principle, and constructs the mathematical model. Section 3 presents the advantages of the proposed approach. Section 4 derives the balance condition, the two-phase circuit decoupling condition, via a mathematical model. Section 5 shows the empirical results. In section 6, this paper reaches its conclusion.

2. Proposed connection scheme

From Figure 2, the h.v. primary windings are composed of windings a_1, b_1, and c_1, which are wye connections, allowing the neutral point to be grounded. The l.v. secondary windings consist of windings a_2, a_3, b_2, c_2, and c_3. The voltage of the output winding is established across the four two-phase terminals be and bd. The l.v. turns are so designed that voltage phasor be is equal to bd. From the geometry of the phasor diagram the quadrature relationship between be and bd will be immediately apparent.

The number of turns in the primary winding is W_1. In the secondary windings, the number of turns of winding a_3 is W_3 and the others are all W_2. Thus, the three-phase windings are an asymmetrical connection. The relationship of number of turns is shown in Eq. (1).



(a) Wiring mode (b) Phasor diagram

Figure 2. Connection and phasor diagrams of the asymmetrical connection.

$$W_3 = (\sqrt{3} - 1)W_2 \tag{1}$$

From Figure 2, we can get

$$\angle abc = 60^\circ, \angle cbd = 30^\circ, \angle ebd = 90^\circ,$$

and the voltage phasor eb is specified as

$$U_{eb} = U_\alpha = (1 + \sqrt{3} - 1)U_{bc} = \sqrt{3}U_{ab}.$$

Similarly, the voltage phasor bd is expressed as

$$U_{bd} = U_\beta = \frac{\sin 120^\circ}{\sin 30^\circ}U_{ab} = \sqrt{3}U_{ab}.$$

3. Advantages

Table 1 shows the performances of several typical balance transformers. As can be seen, the proposed transformer has the following advantages:

1) It has only two or three windings per phase, which is less than that of the impedance-matching balance transformer, so that the winding complication is reduced.

2) The primary neutral is available for earthing, and thus the insulation requirement for primary windings is considerably reduced and the costs are lower.

3) Since windings a_2, b_2, and c_2 form a closed delta connection, shown in Figure 2, the third-harmonic voltages are eliminated by circulation of third-harmonic currents and output voltage waves are sinusoidal.

4) As Figure 2 presents, terminal b in the secondary side can be connected to an electric railway directly, and thus the two autotransformers are saved.

5) The standard three-limb, three-phase core can be employed to simplify manufacturing. The synthetic material utilization ratio (see Section 4.4) is higher than that of the traditional transformers.

Table 1. The performance comparison of several typical balance transformers.

	Scott	Le Blanc	Woodbridge	Impedance-matching	Asymmetrical
Neutral point	No	No	yes	yes	yes
Third harmonic path	No	No	Yes	Yes	Yes
Material utilization	Low, 81.6%	Low, 84.5%	Low, 82.6%	High, 91.95%	High, 94.57%
Extra AT	No	No	Yes	No	No
Complication	Complex	Complex	Complex	Complex	Simple

4. Principles of the asymmetrical connection balance transformer

4.1. Mathematical mode

The ratios of the number of turns are shown as follows:

$$K_1 = \frac{W}{W_1}, K_2 = \frac{W}{W_2}, K_3 = \frac{W}{W_3},$$

where W represents the reference number of turns ($W = W_1$). In Figure 2, $\dot{I}_\alpha$ and $\dot{I}_\beta$ are load currents of the two phases, respectively, while the load voltages are $\dot{U}_\alpha$ and $\dot{U}_\beta$ correspondingly.

According to Figure 2, the current equations are expressed as follows:

$$\begin{cases} \dot{I}_A + \dot{I}_B + \dot{I}_C = 0 \\ \dot{I}_{c2} = \dot{I}_{a2} - \dot{I}_\alpha \\ \dot{I}_{b2} = \dot{I}_{a2} - \dot{I}_\alpha - \dot{I}_\beta \\ \dot{I}_{a3} = \dot{I}_\alpha \\ \dot{I}_{c3} = \dot{I}_\beta \end{cases}, \tag{2}$$

wherein $\dot{I}_A$, $\dot{I}_B$, and $\dot{I}_C$ are three-phase currents in the primary windings. $\dot{I}_\alpha$ and $\dot{I}_\beta$ are two-phase load currents. $\dot{I}_{a2}$, $\dot{I}_{a3}$, $\dot{I}_{b2}$, $\dot{I}_{c2}$, and $\dot{I}_{c3}$ are currents of the secondary windings a_2, a_3, b_2, c_2, and c_3 correspondingly. The secondary winding voltage equations are specified as follows:

$$\begin{cases} \dot{U}_{a2} + \dot{U}_{b2} + \dot{U}_{c2} = 0 \\ \dot{U}_\alpha = -\dot{U}_{a2} - \dot{U}_{a3} \\ \dot{U}_\beta = \dot{U}_{b2} - \dot{U}_{c3} \end{cases}, \tag{3}$$

wherein $\dot{U}_{a2}$, $\dot{U}_{a3}$, $\dot{U}_{b2}$, $\dot{U}_{c2}$, and $\dot{U}_{c3}$ are the phase voltages of the secondary windings a_2, a_3, b_2, c_2, and c_3 correspondingly. The magnetic potential balance equation, ignoring the excitation current, can be rewritten as follows:

$$\begin{cases} \dot{I}_B = \frac{-K_1}{K_2}\dot{I}_{b2} \\ \dot{I}_A = \frac{-K_1}{K_2}\dot{I}_{a2} + \frac{-K_1}{K_3}\dot{I}_{a3} \\ \dot{I}_C = \frac{-K_1}{K_2}\dot{I}_{c2} + \frac{-K_1}{K_2}\dot{I}_{c3} \end{cases}. \tag{4}$$

Based on the multiwinding transformer theory, the transformer equations are obtained as follows:

$$\begin{cases} K_1\dot{U}_B - K_2\dot{U}_{b2} = \frac{\dot{I}_B}{K_1} Z'_{KB12} \\ K_1\dot{U}_A - K_2\dot{U}_{a2} = \frac{\dot{I}_A}{K_1} Z'_{KA12} + \frac{\dot{I}_{a3}}{K_3} Z'_{A213} \\ K_1\dot{U}_A - K_3\dot{U}_{a3} = \frac{\dot{I}_A}{K_1} Z'_{KA13} + \frac{\dot{I}_{a2}}{K_2} Z'_{A312} \\ K_1\dot{U}_C - K_2\dot{U}_{c2} = \frac{\dot{I}_C}{K_1} Z'_{KC12} + \frac{\dot{I}_{c3}}{K_2} Z'_{C213} \\ K_1\dot{U}_C - K_2\dot{U}_{c3} = \frac{\dot{I}_C}{K_1} Z'_{KC13} + \frac{\dot{I}_{c2}}{K_2} Z'_{C312} \end{cases}, \tag{5}$$

wherein $\dot{U}_A$, $\dot{U}_B$, and $\dot{U}_C$ are the phase voltages of the primary side. The impedances are referred to the primary by the turns ratio squared. Z'_{KA12}, Z'_{KA13}, Z'_{KB12}, Z'_{KC12}, and Z'_{KC13} are short-circuit impedances obtained by design calculation or short-circuit test. For example, Z'_{KA12} can be obtained from short circuiting either winding a_1 or a_2 and supplying the other, with the winding a_3 on an open circuit. Z'_{A213}, Z'_{A312}, Z'_{C213}, and Z'_{C312} are equivalent impedances of windings a_2, a_3, c_2, and c_3 correspondingly. The equivalent impedances can be obtained as follows:

$$\begin{cases} Z'_{A213} = 0.5(Z'_{KA12} + Z'_{KA23} - Z'_{KA13}) \\ Z'_{A312} = 0.5(Z'_{KA13} + Z'_{KA23} - Z'_{KA12}) \\ Z'_{C213} = 0.5(Z'_{KC12} + Z'_{KC23} - Z'_{KC13}) \\ Z'_{C312} = 0.5(Z'_{KC13} + Z'_{KC23} - Z'_{KC12}) \end{cases}.$$

The fundamental equations of Eqs. (2)–(5) constitute the mathematical model of proposed transformer, which is the foundation for analysis, design, and manufacturing of the proposed transformer.

4.2. Balance condition

It can be seen from Figure 2 that there is a relationship as follows:

$$\begin{cases} \dot{U}_A + \dot{U}_B + \dot{U}_C = 0 \\ \dot{U}_{a2} + \dot{U}_{b2} + \dot{U}_{c2} = 0 \end{cases}. \tag{6}$$

Supposing $\dot{I}_{a2} = \xi_1\dot{I}_\alpha + \xi_2\dot{I}_\beta$, from Eqs. (2)–(6), we can get (for derivation, see the Appendix on the journal's website):

$$\begin{bmatrix} \dot{I}_A \\ \dot{I}_B \\ \dot{I}_C \end{bmatrix} = \frac{1}{K} \begin{bmatrix} -\xi_1 - \sqrt{3} + 1 & -\xi_2 \\ 1 - \xi_1 & 1 - \xi_2 \\ 1 - \xi_1 & -1 - \xi_2 \end{bmatrix} \begin{bmatrix} \dot{I}_\alpha \\ \dot{I}_\beta \end{bmatrix}, \tag{7}$$

wherein

$$\begin{cases} \xi_1 = \frac{\frac{Z'_{KB12}}{K_2} - \frac{Z'_{KA12}}{K_3} + \frac{Z'_{KC12}}{K_2} + \frac{Z'_{A213}}{K_3}}{(Z'_{KA12} + Z'_{KB12} + Z'_{KC12})/K_2} \\ K = K_2/K_1 = W_1/W_2 \\ \xi_2 = \frac{(Z'_{KB12} - Z'_{KC12} + Z'_{C213})/K_2}{(Z'_{KA12} + Z'_{KB12} + Z'_{KC12})/K_2} \end{cases}. \tag{8}$$

The basic feature of the balance transformer is that the zero sequence current in the neutral condition of the primary winding is always zero irrespective of the load conditions. The sum of three elements in each column of the coefficient matrix on the right-hand side of Eq. (7) should be zero, i.e.

$$\begin{cases} -\xi_1 - \sqrt{3} + 1 + 1 - \xi_1 + 1 - \xi_1 = 0 \\ -\xi_2 - \xi_2 - 1 - \xi_2 + 1 = 0 \end{cases}.$$

This equation can be solved as follows:

$$\begin{cases} \xi_1 = \frac{3-\sqrt{3}}{3} = 0.4226 \\ \xi_2 = 0 \end{cases}. \tag{9}$$

By substituting ξ_1 and ξ_2 into Eq. (8) with its value from Eq. (9), the balance condition is obtained as follows:

$$\begin{cases} Z'_{KB12} - 0.5(Z'_{KC12} + Z'_{KC13} - Z'_{KC23}) = 0 \\ 1.366Z'_{KA12} + 0.634Z'_{KA13} - 0.634Z'_{KA23} - 2Z'_{KB12} - 0.5(Z'_{KC12} + Z'_{KC23} - Z'_{KC13}) = 0 \end{cases}. \tag{10}$$

After satisfying the balance condition, the current relationships are

$$\begin{bmatrix} \dot{I}_A \\ \dot{I}_B \\ \dot{I}_C \end{bmatrix} = \frac{1}{K} \begin{bmatrix} \frac{-2\sqrt{3}}{3} & 0 \\ \frac{\sqrt{3}}{3} & 1 \\ \frac{\sqrt{3}}{3} & -1 \end{bmatrix} \begin{bmatrix} \dot{I}_\alpha \\ \dot{I}_\beta \end{bmatrix}, \tag{11}$$

$$\begin{cases} \dot{I}_{a2} = \frac{3-\sqrt{3}}{3}\dot{I}_\alpha \\ \dot{I}_{b2} = \frac{-\sqrt{3}}{3}\dot{I}_\alpha - \dot{I}_\beta \\ \dot{I}_{c2} = \frac{-\sqrt{3}}{3}\dot{I}_\alpha \end{cases}. \tag{12}$$

Next, supposing that the two-phase load currents are symmetrical, that is

$$\begin{cases} \dot{I}_\alpha = I_2\angle 0^\circ \\ \dot{I}_\beta = jI_2 = I_2\angle 90^\circ \end{cases},$$

from Eq. (11) we can get

$$\begin{bmatrix} \dot{I}_A \\ \dot{I}_B \\ \dot{I}_C \end{bmatrix} = \frac{2\sqrt{3}I_2}{3K} \begin{bmatrix} \angle 180^\circ \\ \angle 60^\circ \\ \angle -60^\circ \end{bmatrix}. \tag{13}$$

Eq. (13) indicates that the primary three-phase currents are balanced with the same magnitude and a 120° phase displacement between any two adjacent phases when the two-phase load currents are symmetrical. Namely, neither zero sequence currents nor negative sequence currents exist in the primary currents in this case.

4.3. The two-phase circuit decoupling condition

For a balance transformer, the changed load in one phase should not affect the operation of another phase. From Eqs. (3) and (5), $\dot{U}_\alpha$ and $\dot{U}_\beta$ can be expressed as follows:

$$\begin{cases} \dot{U}_\alpha = -\dot{U}_{a2} - \dot{U}_{a3} = -\dot{U}_A(\frac{K_1}{K_2} + \frac{K_1}{K_3}) + \frac{\dot{I}_A}{K_1K_2}Z'_{KA12} + \frac{\dot{I}_A}{K_1K_3}Z'_{KA13} + \frac{\dot{I}_{a2}}{K_2K_3}Z'_{A312} + \frac{\dot{I}_{a3}}{K_2K_3}Z'_{A213} \\ \dot{U}_\beta = \dot{U}_{b2} - \dot{U}_{c3} = \frac{-K_1}{K_2}\dot{U}_C + \frac{K_1}{K_2}\dot{U}_B + \frac{\dot{I}_C}{K_1K_2}Z'_{KC13} - \frac{\dot{I}_B}{K_1K_2}Z'_{KB12} + \frac{\dot{I}_{c2}}{K_2K_2}Z'_{c312} \end{cases}. \tag{14}$$

From Eqs. (11) and (12), Eq. (14) can be further expressed as

$$\begin{bmatrix} \dot{U}_\alpha \\ \dot{U}_\beta \end{bmatrix} = \begin{bmatrix} \dot{U}_{\alpha 0} \\ \dot{U}_{\beta 0} \end{bmatrix} - \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} \dot{I}_\alpha \\ \dot{I}_\beta \end{bmatrix}, \tag{15}$$

wherein

$$\begin{bmatrix} \dot{U}_{\alpha 0} \\ \dot{U}_{\beta 0} \end{bmatrix} = \frac{K_1}{K_2} \begin{bmatrix} -1 - \frac{K_2}{K_3} & 0 & 0 \\ 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} \dot{U}_A \\ \dot{U}_B \\ \dot{U}_C \end{bmatrix}, \tag{16}$$

$$\begin{cases} Z_{12} = 0 \\ Z_{21} = \frac{\sqrt{3}}{3K_2K_2}Z'_{KB12} - \frac{\sqrt{3}}{3K_2K_2}Z'_{KC13} + \frac{\sqrt{3}}{3K_2K_2}Z'_{C312} \\ Z_{11} = \frac{2\sqrt{3}}{3K_2K_2}Z'_{KA12} + \frac{2\sqrt{3}}{3K_2K_3}Z'_{KA13} - \frac{1}{K_2K_3}Z'_{A213} - \frac{3-\sqrt{3}}{3K_2K_3}Z'_{A312} \\ Z_{22} = \frac{1}{K_2K_2}Z'_{KC13} + \frac{1}{K_2K_2}Z'_{KB12} \end{cases}. \tag{17}$$

Thus, the two-phase circuit decoupling condition is

$$Z_{12} = Z_{21} = \frac{\sqrt{3}}{3K_2K_2}Z'_{KB12} - \frac{\sqrt{3}}{3K_2K_2}Z'_{KC13} + \frac{\sqrt{3}}{3K_2K_2}Z'_{C312} = 0.$$

That is to say,

$$Z'_{KB12} - 0.5(Z'_{KC12} + Z'_{KC13} - Z'_{KC23}) = 0.$$

It is worth noting that the above equation is the same as the first equation in Eq. (10). Thus, the two-phase circuit is decoupling after satisfying the balance condition.

4.4. Material utilization ratio

The secondary calculated capacity (represented by the number of ampere turns) is:

$$S_j = I_{a3}W_3 + I_{a2}W_2 + I_{b2}W_2 + I_{c2}W_2 + I_{c3}W_2. \tag{18}$$

The secondary output capacity (represented by the number of ampere turns) is:

$$S_2 = 2\sqrt{3}I_2W_2. \tag{19}$$

The copper material utilization ratio is:

$$\eta = S_2/S_j \times 100\% = 2\sqrt{3}/(\frac{5\sqrt{3}+3}{3}) = 89.13\%. \tag{20}$$

The primary copper material utilization ratio is 100%, and therefore the synthetic material utilization ratio is 94.57%.

5. Experiment results

The proposed balance transformer has been implemented on a 1-kVA capacity and is shown in Figure 3. The rated voltages are 380/220 V, respectively. The rated currents are 1.5193/2.2722 A, respectively. A three-phase three-limb core is adopted. The large cross-section wire is adopted to ignore the impact of the winding resistance. A 50-kVA step-down transformer is used as power and the load is adjustable resistance.

In order to verify that the transformer model meets the design requirements, the short-circuit experiments are carried out while the results are displayed in Table 2 (per unit). The design values and the measured values are slightly different due to the restrictions of the factory manufacturing precision, but all errors of short-circuit impedance are less than 4%, which meets the engineering and design requirements (less than 5%) and satisfies Eq. (10).

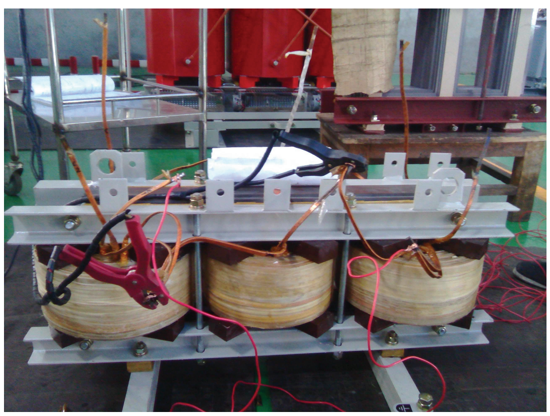
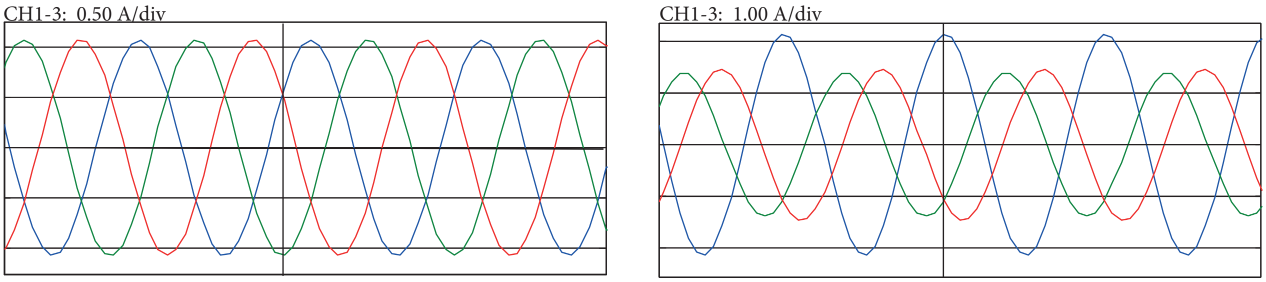


Figure 3. A 1-kVA model transformer.

Table 2. Transformer short circuit experiment.

	X'_{KA12}	X'_{KA23}	X'_{KA13}	X'_{KB12}	X'_{KC12}	X'_{KC23}	X'_{KC13}
Designed value (%)	2.5521	1.7530	4.6699	2.7508	2.5848	1.753	4.6699
Experimental value (%)	2.6135	1.8103	4.7101	2.8204	2.6170	1.801	4.7322
Error (%)	2.4000	3.2000	0.8600	1.8000	1.2000	2.700	1.3000

Real-time power analyzer equipment (HIOKI-9624) was used for online data acquisition. Figure 4 shows the primary current waves under the balanced loads and unbalanced loads simultaneously, while Table 3 shows their positive, negative, and zero sequence currents. In Figure 4a, the primary three-phase currents are symmetrical with the same magnitude and a 120° phase displacement between any two adjacent phases. Table 3 shows that both zero sequence currents and negative sequence currents are nearly zero. Figure 4b and Table 3 show that the primary three-phase currents are asymmetrical with different magnitudes, but the zero sequence current remains nearly zero. The results are quite consistent with the theoretical analysis.



(a) Primary current waves under balanced loads

(b) Primary current waves under un-balanced loads

Figure 4. Transformer experimental graphics.

Table 3. Positive/negative/zero sequence currents in balanced and unbalanced loads.

Conditions	Positive sequence current/A	Negative sequence current/A	Zero sequence current/A
Balanced loads	2.14	0.01	0.010
Unbalanced loads	1.6	0.53	0.015

Table 4 records the operational experimental results of the proposed transformer when the rated load in α phase keeps fixed and the load in β phase reduces from the rated load to no-load gradually. It can be seen from Table 4 that the two-phase load voltages remain unchanged in the process. This indicates that the circuits of the α and β phases are decoupling. As for the three-phase currents or voltages, they gradually change from equal to unequal because of the negative sequence components, but zero sequence current is still near zero. The maximum value of the zero sequence currents is found to be 0.0184 A, while the ratio with the corresponding three-phase average current is 0.018, which is less than 2%. This indicates that the balance transformer can effectively eliminate the zero sequence current and proves the correctness of the theoretical analysis.

Table 4. The data of the transformer load experiments.

Operation mode	α phase current/A	b phase current/A	a phase voltage/V	b phase voltage/V	A phase current/A	B phase current/A	C phase current/A	A phase voltage/V	B phase voltage/V	C phase voltage/V	Zero sequence current/A
1	2.26	2.27	218.6	218.6	1.52	1.52	1.50	218.5	218.3	218.9	0.0100
2	2.26	1.78	218.9	218.8	1.52	1.28	1.28	218.7	218.3	219.1	0.0120
3	2.26	1.29	218.4	219.4	1.52	1.06	1.07	218.3	218	219.9	0.0143
4	2.26	0.9	218.7	219.3	1.52	0.91	0.92	218.6	217.5	220.3	0.0173
5	2.26	0.71	218.8	219.6	1.51	0.85	0.87	218.6	217.3	220.7	0.0174
6	2.28	0.00	218.7	219.8	1.51	0.77	0.76	218.6	217.1	221.1	0.0184

6. Conclusion

The analysis method proposed is suitable for analyzing other transformers. The proposed transformer has several merits, such as simple structure, easy manufacturing, excellent all-around performance, and high utilization rate of material. Furthermore, this transformer can eliminate the zero sequence currents and suppress negative sequence currents considerably, which is especially useful when a single-phase load or two-phase load is necessarily required. It has broad prospects to develop the traction power supply.

Acknowledgment

The authors would like to give thanks for project support by the National Natural Science Foundation of China under Grants 51077044 and 51077045, the Hunan Natural Science Foundation 12JJ2034, and the Hunan Science and Technology Project 2012FJ4372. The authors are also grateful to engineer Siyong Ye for his great help in transformer experiments.

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A. Appendix

From Eq. (5), we can get

$$\begin{cases} K_1\dot{U}_B - K_2\dot{U}_{b2} = \frac{\dot{I}_B}{K_1}Z'_{KB12} \\ K_1\dot{U}_A - K_2\dot{U}_{a2} = \frac{\dot{I}_A}{K_1}Z'_{KA12} + \frac{\dot{I}_{a3}}{K_3}Z'_{A213} \\ K_1\dot{U}_C - K_2\dot{U}_{c2} = \frac{\dot{I}_C}{K_1}Z'_{KC12} + \frac{\dot{I}_{c3}}{K_2}Z'_{C213} \end{cases}. \tag{A.1}$$

With summation of Eq. (A.1), we can obtain

$$\frac{\dot{I}_A}{K_1}Z'_{KA12} + \frac{\dot{I}_B}{K_1}Z'_{KB12} + \frac{\dot{I}_C}{K_1}Z'_{KC12} + \frac{\dot{I}_{a3}}{K_3}Z'_{A213} + \frac{\dot{I}_{c3}}{K_2}Z'_{C213} = 0. \tag{A.2}$$

Substituting Eq. (4) into Eq. (A.2) yields the following expression:

$$\frac{\dot{I}_{a2}}{K_2}Z'_{KA12} + \frac{\dot{I}_{a3}}{K_3}(Z'_{KA12} - Z'_{A213}) + \frac{\dot{I}_{b2}}{K_2}Z'_{KB12} + \frac{\dot{I}_{c3}}{K_2}(Z'_{KC12} - Z'_{C213}) + \frac{\dot{I}_{c2}}{K_2}Z'_{KC12} = 0. \tag{A.3}$$

Substituting Eq. (2) into Eq. (A.3), we can get

$$\dot{I}_{a2}(\frac{Z'_{KA12} + Z'_{KB12} + Z'_{KC12}}{K_2}) = \dot{I}_{\alpha}(\frac{Z'_{KB12}}{K_2} - \frac{Z'_{KA12}}{K_3} + \frac{Z'_{KC12}}{K_2} + \frac{Z'_{A213}}{K_3}) + \dot{I}_{\beta}(\frac{Z'_{KB12} - Z'_{KC12} + Z'_{C213}}{K_2}). \tag{A.4}$$

Supposing that $\dot{I}_{a2} = \xi_1\dot{I}_{\alpha} + \xi_2\dot{I}_{\beta}$, by substituting Eqs. (2) and (A.4) into Eq. (4), Eq. (7) can be obtained.